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COMPUTATIONAL ASTROPHYSICS RELATING TO THE INTERSTELLAR MEDIUM -- PROBLEMS AND PROSPECTS FOR THE 1980'S

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Computational Astrophysics Relating to the Interstellar Medium -- Problems and Prospects for the 1980's

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The general goal of research on the interstellar medium is to understand the structure and dynamics of the interstellar gas. This subject is important for three reasons. First, the classic tracers of the spiral structure of galaxies are related directly to the gaseous component of galactic disks. Therefore an understanding of the dynamics of the gas is essential in interpreting observations of spiral galaxies. Second, radio continuum observations relate to the magnetic field, which is frozen into the gas under most circumstances. Hence these observations must be interpreted using magnetohydrodynamic models. Third, the initial conditions for star formation are determined by the structure and dynamics of the interstellar gas. In this way gas dynamics plays an essential role in understanding the relative numbers of binary and single stars, the formation of planetary systems, and even the evolution of the stellar content of galaxies.

The equations of gas dynamics are nonlinear. For this reason, only small amplitude disturbances can generally be treated by analytic methods. Such methods can be used to predict the instability of a given state of the gas, but only indicate the character of the final state towards which such an unstable gas would evolve. Consequently, computer simulations play an indispensable role in our understanding of gas dynamics. These simulations are limited only by the approximation that the structure of the gas within small fluid elements, or zones, is especially simple (a constant, or a linear function, for example). When the zones are infinitesimal, this is the same assumption used in deriving the fluid equations in the first place; thus as the zones are made smaller the numerical solution converges to that of these differential equations. However, for zones of finite size this approach results in unphysical error terms entering the effective set of partial differential equations actually solved. In order to reduce these errors so that they do not affect the solution it is necessary to use a combination of a fine grid of zones and an accurate numerical method.

The main analytic work on the dynamics of the interstellar gas describes a variety of instabilities which result in structure within the gas -- the Jeans instability, thermal instability, and Parker instability. Each of these has been treated in the large amplitude regime only through computer simulation. An instability which remains to be well treated numerically is that which gives rise to spiral structure in galaxies. Here a complete description must involve both gas dynamics and stellar dynamics, coupled by the force of gravity. Simulations of the stellar dynamics will be discussed by Dr. Sanders. Suffice it to say that such calculations are the most expensive yet attempted. Gas dynamics in spiral waves has been treated by standard numerical methods, but this approach is limited by the artificial transport of angular momentum which results from the numerical method and which swamps the angular momentum transport caused by the spiral wave. Realistic simulations of disk galaxies, coupling stellar and gas dynamics can be expected in the 1980's, but these calculations will require considerable programming effort and considerable machine time, even on computers as fast as a Cray-I.

In comparison to simulations of galaxies, magnetohydrodynamic (MHD) calculations are even more complex. Very little work in this area has been performed, despite the development of computational methods in the magnetic fusion program. The apparent reason for this lack of work is that these problems are very difficult and costly. MHD calculations are difficult for several reasons. First, there are 8 equations to solve rather than 4, and one, Poisson's equation, is non-local and demands an implicit technique or a spectral method. These methods, which tend to involve matrix inversions, are extremely expensive.

A result of the large number of equations to be solved is that MHD systems can oscillate in many different ways. This causes great confusion and makes an intuition for MHD flows nearly impossible to develop. In simple gas dynamics there are only two ways to send a signal from one point to another -- to send material or to send an acoustic wave. In MHD, signals can be sent in several different ways, and these signals will all travel at different speeds. What is worse, these signals can interact in complicated ways. An example is the generation of Alfven waves by particles which stream along the magnetic field faster than the Alfven wave speed. The wave generation causes the particles to stream along the field less rapidly. It is impractical to expect an MHD code to produce such subtle wave interactions automatically within the context of some larger calculation. Instead one would like to solve some modified set of differential equations which would account for these effects explicitly. Such equations have not yet been formulated.

The multiplicity of wave speeds in MHD problems can cause yet other difficulties. In a specific problem it can happen that only certain types of signals are important, but that a calculation is forced to use a small time step for numerical stability because irrelevant, fast signals are still described by the equations. An example is the fast propagation of Alfven waves in regions where the gas density is very low, and where nothing interesting may actually be happening. This problem requires some special treatment or it requires an implicit calculation. The latter approach would be extremely expensive.

Perhaps the most vexing feature of MHD problems is their lack of symmetry. It is commonly the case that all but extremely contrived magnetic field configurations demand a fully three-dimensional treatment. Two-dimensional MHD calculations already tax the largest and faster computers, and three-dimensional problems are at present prohibitively expensive.

Despite all these negative features of MHD problems, many are of great astrophysical interest and are therefore worth the substantial efforts of men, women, and machines which will be required for their solution. In the 1980's, machines and numerical techniques will surely be developed, driven by the magnetic fusion program, which will make solution of such astrophysical problems possible. A few problems whose solution we may look forward to are: the non-linear development of Parker's instability, transport of low energy cosmic rays from supernovae to heat the surrounding gas, generation of a galactic magnetic field from differential rotation of the disk, gravitational collapse of gas clouds with frozen-in magnetic fields. Some work on the last of these problems has already been done, and we can expect a great deal more in the next decade. A wide open area for MHD simulations is the study of beams of hot plasma from the nuclei of active galaxies -- their generation, collimation, and interaction with the surrounding intergalactic medium.

In studying the star formation process, we have so far merely scratched the surface. We can expect major developments in this area in the 1980's, but the ultimate goal is far off indeed. We desire an understanding of the process whereby normal interstaller material, as observed with radio telescopes, is transformed into multiple star systems, or into stars with planetary systems. Analytic work has been limited to arguments based upon the virial theorem and to linear analysis of thermal and gravitational instabilities. Computer simulations have given us a very detailed understanding of spherical gravitational collapse. Serious work on the simulation of axisymmetric collapse of rotating clouds is just beginning. Present computers and numerical methods allow the collapse to be followed while the gas remains optically thin, and hence isothermal. Beyond that point extreme numerical difficulties set in which are related to the very different spatial and temporal scales characterizing phenomena such as sound wave propagation, radiation diffusion, and viscous dissipation in various regions of the gas cloud.

Successful two-dimensional simulations of gravitational collapse of rotating clouds to form, say, protostellar cores surrounded by protoplanetary disks will require the most sophisticated numerical techniques which now exist and the largest, fastest computers. In fact, such calculations might well require more than this. We can expect some advances in this area in the 1980's, although at present levels of financial support the progress will certainly be slow. To be specific, such a calculation would require a hybrid implicit-explicit numerical technique for the hydrodynamics, coupled to implicit radiation transport. Computational zones with built-in internal structure of an appropriate kind would be needed to treat the tremendous changes in density and temperature. In addition, a multifluid calculation would be required so that regions in which vastly different physics is dominant (e.g. hydrostatic versus collapsing, ionized versus unionized, etc.)

could each be accurately treated within a single calculation. No such program now exists, and it is debatable that the machine exists which could perform the calculation in a reasonable time (i.e. a day).

Unfortunately, many of the gas dynamic simulations which we would like to perform are three-dimensional. This is utterly beyond the reach of present techniques and machines. In the 1980's we are likely to investiage 3-D situations by a series of 2-D simulations, much as 2-D situations have been studied by using 1-D calculations in the past. Thus, a calculation yielding a protoplanetary disk from a rotating gas cloud cannot be expected to yield Jupiter as well. The non-axisymmetric instabilities responsible for planet formation will no doubt be studied by simulations of an isolated, thin disk.

In the 1980's, increases in computer power and in program sophistication will allow us to treat more and more interdependent processes in a single calculation. For simulations of galaxies, we may hope to combine stellar dynamic with gas dynamic models. We may also hope for combined treatments of pressure, gravitational, and magnetic effects in MHD simulations of gaseous disks of galaxies and of collapsing interstellar clouds. In the area of star formation we may hope to see pressure, rotation, gravity, and radiation transport combined in a single calculation. For magnetic fields to be added to this we will probably have to wait for the 1990's.

The ambitious projects listed above represent the potetnial for advance in the 1980's. The necessary machines and numerical techniques will almost certainly exist in the coming decade. However, to pursue these projects will require substantial investment in manpower and computer power which may not be forthcoming. Hopefully, the importance of the science involved and the unique capabilities of the simulation approach will generate the necessary interest in the astronomical community to get this work underway.

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